

(Anacardium occidentale)

Original Research Article

Estimating ^{the} area and dry mass of cashew ^{leaves} leaf: Effect of tree position within a plantation near Parakou, Benin

Abstract.

Background and Aims: Accurate and non-destructive methods to determine individual leaf areas and dry mass of plants are very important because they are key parameters linked to plant production and they are used in functional-structural plant models to simulate plant growth. This paper describes an investigation of the variation in cashew leaf dimensions at different sites within a plantation with the aim of developing a model for calculating leaf area and dry mass.

Methods: Five positions (south, central, north, east and west) were considered in an eight years old rectangular cashew plantation, with an area of 3.5 ha. Two trees were selected randomly by location. Their crown was divided vertically into three zones. Within each zone, 60 leaves were collected randomly on different categories of axis of the tree. The length, width, area, and the dry mass of each leaf were measured.

Key Results: The longest leaves were obtained in the north, center and south of the plantation (15.27 cm). The leaves of trees located in the south of plantation were the largest (9.6 cm) and had the largest areas (109.1 cm²). The largest quantities of dry mass were obtained from the leaves of the trees located in the south and in the east of the plantation (1.35 g per leaf). The best models according to adjustment and prediction qualities were in all cases as such $S^2 = a \ln(LW) + b$ for leaf area and $m^2 = a \ln(LW) + b$ for dry mass.

Conclusions: These data demonstrate that there is an important variation in leaf size and dry mass according to a tree position in the plantation. Therefore, it is important to take into account this variability in the sample constitution when trying to estimate leaf area and dry mass.

Key words: Leaf area, dry mass, tree position, sunlight, cashew, models, Benin.

29 Introduction

30 Leaves are one of the main plant components involved in plant biomass production through
 31 photosynthesis [1] (Tondjo *et al.* 2015). On an individual plant scale, the leaf area and
 32 specific leaf area, i.e. the ratio between leaf area and dry biomass, have been shown to be
 33 good indicators of plant productivity, for instance on poplar clones [2] (Marron *et al.*, 2005).
 34 Leaf area is furthermore an important variable for most ecophysiological studies in terrestrial
 35 ecosystems concerning light interception, evapotranspiration, photosynthetic efficiency,
 36 fertilizers, and irrigation response and plant growth [3] (Blanco and Folegatti, 2005). ~~In~~
 37 ~~addition,~~ ^{also} the leaf area is required for assessments ^{of} fruit growth, evaluation of training and
 38 pruning systems, and estimation of pest population densities ([4], [5]) (Lang, 2000, 2005).
 39 Functional-structural plant models (FSPM) [6] (Fourcaud *et al.*, 2008) can facilitate the
 40 understanding of the functional links among leaf characteristics, carbon production and
 41 allocation. Consequently, the easy, economic, and precise estimate of leaf area or dry mass of
 42 leaf has been a concern to plant scientists for a long time. The most common approach is to
 43 develop ratios and regression estimators by using easily measured leaf parameters such as
 44 length and width [7] (Kvet and Marshall, 1971). Comparing several non-destructive models
 45 of leaf area of taro, Lu *et al.*, [8] (2004) proposed that the simple and linear relationships
 46 between leaf area and leaf dimensions (length, width) could be useful for non-destructive
 47 estimation of leaf area. Thus, non-destructive models for leaf area determination have been
 48 established for many species such as maize [9] (Stewart and Dwyer 1999), bean [10] (Bhatt
 49 and Chanda, 2003), taro [8] (Lu *et al.*, 2004), kiwi [11] (Mendoza-de Gyves *et al.*, 2007),
 50 ginger [12] (Kandiannan *et al.*, 2009) and watermelon [13] (Rouphael *et al.*, 2010). Similarly
 51 within the framework of fruit trees, several combinations of measurements and models
 52 relating length and width to area have been developed for several fruit trees, such as grape
 53 ([14], [15]) Montero *et al.*, 2000; Williams and Martinson 2003) and avocado [16] (Uzun and

(*Anacardium occidentale* L.)

54 Celik, 1999). However, models to estimate the leaf area of cashew are almost absent in the
55 literature.

56 The cashew tree is native to the Caribbean and the ^{northeastern} North East of Brazil. It is now widely
57 cultivated in all tropical areas, such as Africa, Caribbean, Brazil ^{and} Northeast, Southeast Asia
58 and India. The economic importance of this plant lies mainly in its fruit (cashew nuts). For
59 example, in Benin, cashew nuts ^{are} the second export crop after cotton and its importance is
60 increasingly growing in agricultural production systems [17] (PADSE, 2003). Cashew
61 accounted for 8% of the total value of exports in 2008, 7% of agricultural GDP and 3% of
62 GDP [18] (Tandjiekpon, 2010).

63 ~~Moreover,~~ the predictive accuracy of non-destructive models of leaf area or biomass depends
64 on the variation of the leaf shape within the same plant and between accessions [19] (De
65 Swart *et al.*, 2004). This variation may also be related to environmental factors including the
66 quantity of sunlight captured by the plant. Indeed, plants produce several types of leaves
67 during their development. The first few true leaves produced are usually smaller, simpler, and
68 anatomically different from leaves produced later in development [20] (Poethig, 1997).
69 Change in shape and size of successive leaves on a plant are related to physiological changes
70 associated with increasing age of the plant [21] (Esau, 1965), interaction between the shoot
71 apical meristem and the developing leaf primordial [22] (Byrne *et al.*, 2001), ~~and~~ genetically
72 ~~regulated programs of~~ ^{controlled} shape maturation and a variety of environmental factors [20] (Poethig,
73 1997). Therefore a good estimate of the production model requires accurate estimation of the
74 area and mass of leaves taking into account any possible variability.

75

76 The aim of this study is thus to develop a non-destructive estimation model of the area and
77 dry mass of leaves of cashew taking into account the trees ^{location} position in a ^{plantation} planting for a better
78 understanding of the variability of ^{dry matter} matter production by photosynthesis.

79 **Material and methods**

80 **Data collection**

81 The cashew ^{plantation} ~~tree~~ selected for the study was 8 years old, ^{encompassing a} rectangular ~~and with an~~ area of 3.5 ha
 82 ^{with} and a density of 400 trees/ha. It is located ^{near city} ~~in the district~~ of Parakou, ^{Benin} (9°20' north latitude and
 83 2°35' East longitude) ^{where}. The climate is of Sudanese type with a rainy season (June to
 84 November) and a dry season (December to May). The average annual rainfall varies from
 85 1100 to 1200 mm per year. ^{and} The annual average temperature varies between 26° C and 30° C.
 86 The warmest month of the year is February while the coolest ^{is} August. The relative humidity
 87 varies from 15% in the dry season (January-February) to 99% in the rainy season (August-
 88 September) while the annual average insolation varies between 2,200 and 2,400 hours.

89 The plantation was divided into five zones (south, central, north, east and west) according the
 90 direction of solar radiation movement. In each zone two trees were randomly selected.
 91 Selected trees have an average diameter of 20.68 cm and an average height of 5.15 m. The
 92 crown of each tree ^{was} ~~has been~~ divided vertically into three zones. ^{?? - What were they?} In each zone, 60 leaves were
 93 collected from random manner taking into account the possible wide range of dimensions for
 94 the categories of axes. In total, a sample of 180 leaves were collected per tree. On each leaf,
 95 the following data were collected:

- 96 - the length of the leaf representing the distance between the top of the leaf blade and
- 97 stipule of the leaf (petiole base);
- 98 - the width of the leaf corresponding to the leaf width measured at half of the length;
- 99 - the leaf area representing the entire area occupied by the blade. Each leaf was
- 100 photographed with a digital resolution of 18 Mega pixel camera. The leaf area

I assume the zones are based on the aspect slopes - - - lower, middle & upper?

101 corresponding to each image obtained was determined using the Mesurim Pro version
102 3.4 software;

103 - the dry mass is the mass of the leaf when it is free of all the amount of water it
104 contains. To determine the mass, each leaf was dried in an oven at 103 °C for 24
105 hours and then stored in a room heated closed storage for 24 hours. They were then
106 weighed using a balance to 0.01 g accuracy.

107

108 **Data analysis**

109 Initially, data was described. Secondly, the effect of tree position on the dimensions of the
110 cashew leaf was evaluated using analysis of variance method with factors for the position
111 (five modalities: south, central, north, west and east) and the trees. The Newman-Keuls test
112 was also used to structure the mean in case of significant difference. The method of
113 covariance was used to test the effect of the position on the estimation of the leaf area and dry
114 mass. The position was considered as a dummy variable in the models studied. The
115 estimation models of leaf area and dry mass were established using the linear regression
116 method. In this context, different types of models were tested (Table 1). The Box and Cox
117 transformation was applied to the response variable in order to make valid the conditions of
118 application of the method. The Box-Cox transformation is indeed a transformation of the
119 dependent variable that can be closer to the normal distribution and make constant variances.

120

121 The prediction quality of the models was evaluated by the cross-validation method in order to
122 limit problems like overfitting. Indeed, cross-validation tests the predictive accuracy of a
123 model in a testing dataset relative to the predictive accuracy of the training dataset from
124 which the model was established. Ideally, with a large enough sample, a proportion of

125 observations is assigned to the training dataset and the remaining observations are assigned to
 126 the testing dataset. The model is constructed using the observations of the training dataset,
 127 and the predictive power is tested using observations from the testing dataset. The prediction
 128 error is estimated by calculating ^{on the testing dataset, the mean square error.} ~~The sample~~ ^{Since}
 129 ^{in this study was} size ~~is~~ ^{not} large enough ^{in the context of this study,} the approach used was leave-on-out cross
 130 validation method which ~~consist to~~ ^{consists of} dividing the original sample into ⁿ samples (n is the sample
 131 size), then select ^{one} of the n samples as the validation set and the (n-1) ^{uses remaining as} ~~other~~ samples ^{formed}
 132 the training set. The mean square error was calculated. The operation was repeated n times by
 133 selecting another validation sample from the (n-1) samples which have not yet been used for
 134 model validation. The average of n mean square errors were calculated to estimate the
 135 prediction error.

136 Table 1

137

138 Results

139 Description of data

140 ^{The average} Leaf length ~~is on average~~ ^{ranged} between 13.70 cm and 15.49 cm, ~~respectively~~ with an average
 141 error of 0.12 cm and 0.15 cm (Table 2). The ^{longest leaf} ~~highest~~ length was obtained ^{occurred} on the leaves of the
 142 trees situated ^{in the section} north while the shorter length was obtained ^{occurred on trees} on the leaves of trees located ⁱⁿ to the
 143 west. ^{section} With regard ~~the~~ ^{The average leaf width ranged from} width of the leaves, they vary in average of 8.37 cm to 9.60 cm. ^{found on trees in} The
 144 ~~greatest width was achieved on the leaves of the trees to the south and the lowest value was~~
 145 ~~obtained on the leaves of trees located to the west.~~ As for the leaf area, values were on
 146 ^{the} average ^{ranged} between 66.77 cm² (obtained in the east) and 109.14 cm² (obtained in the south).
 147 The ^{mean} dry mass of the leaves ^{ranged} varies ~~on average~~ from 1.03 (obtained in the west) ^{to} and 1.29 g

148 (obtained in the south). The variability was of same order of magnitude for most positions
 149 regardless of the parameters considered.

150 Table 2

151

152 Effect of the trees position on the characteristics of the leaves

153 Evaluation of the effect of the tree position in the planting with respect to the solar radiation
 154 on the features of the cashew leaf (~~Table 3~~) showed that the leaves having larger dimensions
 155 and greater dry weight were obtained from trees located in the south area of the plantation (~~15~~
 156 ~~cm in length, 9.6 cm in width, 109.1 cm² for the area and 13 g/leaf to the dry mass~~). Whereas,
 157 the leaves of the trees from the west side of the plantation are small and have the lowest value
 158 of dry mass (~~13.7 cm in length, 8.4 cm in width, 71.4 cm for area and 1 g/leaf to the dry~~
 159 ~~mass~~). We also note a slight gradient to lower values from south to north and from east to
 160 west.

161 Table 3

162

163 Estimation of leaf area and dry mass

164 The results of analysis of variance ~~previously obtained, showed~~ ^{demonstrated} that tree position influenced
 165 the area and dry mass of the leaves. These effects were confirmed by analysis of covariance
 166 whose results have not been presented in the paper for brevity. Indeed, the results of
 167 covariance analysis showed that the dummy variable had a significant effect in each model, ^{thus}
 168 ~~These results suggested~~ ^{may} that estimating the leaf area and dry mass must be ^{performed by} ~~done~~ for each tree
 169 position in the plantation.

170 ~~Examining the results~~, ^{free results} regardless of the position, showed that the best models from the point
 171 of view of fit quality and prediction quality were in the form $S^i = a \ln(LW) + b$ for leaf area
 172 (Table 4) and in the form $m^i = a \ln(LW) + b$ for dry mass (Table 5). ~~Indeed~~, for these models
 173 The adjusted R^2 values are highest, indicating that they were relatively well adapted to ^{the} data. In
 174 addition, in terms of prediction, the mean square errors obtained by cross-validation were
 175 lowest.

176 ~~Moreover~~, ^{model's} the diagnostic results of the residuals (Figures 1 and 2) comply with the conditions
 177 of applications of the method. ^{heavily indicating} Thus, the histograms indicated no potential outliers in the data.

178 ~~The~~ Normal probability plot of the residuals ^{were} showed almost linear plots, ^{which is} consistent with a normal
 179 distribution. Diagrams ^{of the} residual values based on the adjusted values ^{displayed} presented a random
 180 pattern, suggesting that the residuals had constant variance. Graphs of the ^{residuals with the predicted} ~~order according to~~
 181 ^{and the observed} ~~the residual~~ values showed no particular pattern. Therefore, these models were those that best

182 predicted the area and the dry mass of a new leaf from a tree located at a given position of the
 183 planting.

184 Although the models of form $S^i = aLW + b$, $S^i = aL^2 + b$ and $S^i = aW^2 + b$ ^{for} leaf area ~~in the~~
 185 ~~one part~~ and form $m^i = aLW + b$, $m^i = aL^2 + b$ and $m^i = aW^2 + b$ for dry mass, ~~on the other~~
 186 ~~hand~~, ^{to that} had relatively high adjustment qualities, near of the selected models, they nevertheless
 187 presented poorer predictive qualities. The ~~form~~ models $S^i = aL + b$, $S^i = aW + b$, $S^i = a \ln(L) +$
 188 b and $S^i = a \ln(W) + b$ ^{for} leaf area ~~of the one part~~ and form $m^i = aL + b$, $m^i = aW + b$, $m^i =$
 189 $a \ln(L) + b$ and $m^i = a \ln(W) + b$ for ~~dry mass~~, ~~on the other hand~~, ^{only} gave intermediate results.

190 **Table 4**

191 **Table 5**

192 **Figure 1**

193 **Figure 2**

194 **Discussion**

195 In this study, the effect of the cashew tree ^{location} position in the plantation ^{was evaluated.} was evaluated on the
196 estimation of leaf area and of the dry mass of the leaves. In the literature, several models
197 were described to estimate the leaf area ^{of different species} For many plants, these models ^{which,} were generally ~~the~~
198 functions of the length and width, but very little information was available for cashew.

199 ^{consistent? - species have different leaf morphology. Only other species mentioned is grape + avocado}
200 The average values obtained for the ^{foliage} leaves dimensions for different tree ^{locations} positions in the
201 plantation were consistent ^{for other species} with those reported in the literature, ^{the length varies between 10}
202 and 20 cm and width varies between 6 and 10 cm in width. Similarly the values of the leaf

203 area are consistent with those reported by Archak *et al.* [23] (2003) who reported leaf size of
204 87.2 cm² and a range of 51.4 to 174.3 cm². Assessing the effect of the trees ^{position} on the
205 characteristics of the leaf showed a significant effect on both ^{dimensions and} the dimensions of the leaf on its

206 dry mass. The heaviest leaves and large ^{at} dimensions ^{leaves occurred} were obtained in the south, and lighter
207 and smaller ^{at} dimensions ^{leaves occurred} were obtained in the east and west of the plantation. ^{sections} The quantity of
208 dry mass produced per leaf follows the same trend. The function of leaves is to gather energy

209 from sunlight, and exchange carbon dioxide and oxygen with the atmosphere through
210 photosynthesis. The anatomy and growth of leaves is complex. The soil is more or less

211 homogeneous in the plantation and ^{the entire plantation received} trees receiving the same silvicultural treatment, ^{the results}
212 can be explained ^{therefore,} among other things by the fact that trees located in the south of plantation
213 have more sunlight and therefore produce more dry mass ^{is because it receives more sunlight} for their growth and development.

214 Indeed, a leaf subjected to a given illumination (useful quantum light for photosynthesis)
215 will absorb a ^{given} certain quantity of carbon dioxide from the air (CO₂) and following various
216 photochemical processes and dark reactions produce carbohydrate base compounds ^{for} of the
217 plant growth [24] (Jones, 1992). However, a key feature which influences the interception of
218 photosynthetic radiation of a vegetation canopy is the inclination and azimuth of the leaves

What is PAR

219 [24] (Jones, 1992). Under natural conditions, the total incident radiation (PAR) at a given

220 time on a canopy comes from all directions of the celestial canopy in varying quantities

221 according to each of these directions [25] (Deneroy *et al.*, 2002). The canopy is not isotropic, and the

222 interception is different for each incidence angle of the radiation [24] (Jones, 1992). In

223 addition the angular distribution of the incident radiation intensities also vary over time, depending

224 especially along the height of sun in the sky [25] (Deneroy *et al.*, 2002). Furthermore,

225 observations in the field showed that natural vegetation located south of the plantation was

226 more open with the presence of yam fields in particular. Niinemets *et al.* [26] (2007) reported

227 that variation in leaf size is associated with major changes in within-leaf support investments

228 and in large modifications in integrated leaf chemical and structural characteristics.

229 The variability of the leaf area and dry mass according to the position measured by the

230 coefficient of variation, in the order of 30% suggest that the shape of the leaf and therefore

231 the quantity of dry mass content varies according to the position of the leaf on the tree. This

232 result is consistent with other studies those known in the literature ([21] Esau, 1965; [27] Wardlaw, 1968;

233 [19] De Swart *et al.*, 2004). Other authors like Verwijst and Wen [28] (1996) and De Swart *et*

234 *al.* [19] (2004) also mentioned a difference in shape between the leaves on the main stem and

235 those made by the lateral branches, respectively in *Salix viminalis* and *Capsicum annuum*.

236 However, Tondjo *et al.* [1] (2015) did not detect a difference between the shape of the leaves

237 from the stem and leaf shape of the branches in teak. These latter authors found out

238 differences between the dry mass of the leaves from the stems and those of the branches.

239 Similar results were also obtained by Leroy *et al.* [29] (2008) who mentioned the existence of

240 the variability in leaf mass area linked to the architectural position and the axis category of

241 the parent shoots.

242 Evaluation of the influence of the tree positions on estimating the leaf area and dry mass of

243 leaves showed a significant effect thus confirming the previous results. In fact, the

Similar, meaning no difference in ~~dry mass~~ leaf shape but differences in leaf dry mass? Please clarify....

need to explain relevance

unclear? don't understand what you are saying

position on tree or in plantation?

but they did find

? what previous results??

244 comparison in pairs of the five estimation models for each characteristic (leaf area and dry
 245 mass of the leaf) showed that different models should be used for each position. ^{Regardless} ~~Whatever~~ the
 246 ~~considered~~ position, the models ^{that best} ~~better~~ predict the leaf area and dry mass of a new leaf in a
 247 plantation of cashew. ~~From measurements of the length and width~~ are logarithmic models of
 248 the form $S^i = a \ln(LW) + b$ for leaf area and ~~the form form~~ $m^i = a \ln(LW) + b$ for dry mass. In
 249 terms of fit ~~quality of the data~~, the models obtained are significant and generally satisfactory
 250 (R^2 varies from 0.51 to 0.86, for leaf area and 0.30 to 0.80 for the dry mass). Moreover, the
 251 prediction errors obtained by cross-validation are rather low and vary from 0.0001 to 0.2978
 252 for leaf area and from 0.0001 to 0.0116 for dry mass. Prediction ^{accuracy} ~~quality~~ of leaf area of a new
 253 leaf are more ^{accurate} ~~efficient~~ for models established in tree positions in the north, center and east. It
 254 is less ^{accurate} ~~efficient~~ for those in tree position of south and west. ^{In} ~~Regarding~~ ^{leaf} ~~the~~ dry mass, all
 255 models obtained predict efficiently the dry mass of a new leaf, although a number of these
 256 models have a relatively poorer fitting quality. ^{Accordingly,} ~~These results confirm that the~~ leaf area and
 257 dry mass ~~of the leaf~~ can be estimated with good accuracy from the maximum length and ~~the~~
 258 ~~maximum~~ ^{leaf blade} width of the sheet. Unlike the logarithmic models obtained in this study, Murthy *et*
 259 *al.* [30] (1985) had determined a linear relationship between leaf area and the product of the
 260 length and width for the ^{what species?} same species. The differences between the models can be linked
 261 among other to climate effects, ^{what climate effects?} variety and especially the fact that these authors did not used
 262 to their selection, a criterion based on the assessment of the prediction quality on new leaf. ^{variety of what?}
 263 Non-destructive estimation models of leaf area based on the measurements of linear
 264 dimensions such as length and width have been established for many species such as avocado
 265 [16] (Uzun and Celik, 1999), banana [31] (Potdar and Slovak, 1991), kiwi [16] (Uzun and
 266 Celik, 1999), maize [9] (Stewart and Dwyer, 1999) and sunflower [32] (Bange *et al.*, 2000).
 267 Other authors have ^{developed} ~~seen~~ the power ^{function} ~~models~~ of ~~the~~ length and/or width as most suitable for
 268 plants such as black pepper [33] (Kandiannan *et al.*, 2002), vines [15] (Williams and

The word "position" has been used to describe location in the plantation, and location in the tree. This has

become confusing as to which you are referring? Need to clarify.

what does this mean? meaning the variables are significant? ($p < .05$, $F > .0001$)

How do you explain this

between your models and the models of Murthy *et al.* (1985)

very unclear?

269 Martinson, 2003), the dwarf coconut [34] (Souza *et al.*, 2005), jatropha [35] (Pompelli *et al.*,
 270 2012) and teak [1] (Tondjo *et al.*, 2015). Others ~~again were established~~ ^{have been developed} models from a single
 271 characteristic of the leaf (length or width). Thus, Reynolds [36] (1971) proposed two models
 272 based on each of the two characteristics (length or width) to predict leaf area of a cocoa leaf.
 273 Kobayashi [37] (1988) used the length to predict leaf area of a guava leaf, and Willaume *et*
 274 *al.*, [38] (2004) ~~also estimated leaf area of the apple leaf from measuring~~ only the length of
 275 the leaf. In this study, power models and models based on the use of a single characteristic
 276 (length and width) ^{do not perform well} ~~are less good~~ in terms of ^{prediction} quality. The differences between the
 277 models ^{are due to differences in} ~~can be related to~~ the conditions of the study environment and the specificity of the
 278 leaf shape of the species studied. The same types of models were obtained for all ^{plantation locations} positions,
 279 suggesting that ~~grow~~ cashew leaves retaining their shape regardless of the ^{location} position. These
 280 ^{of this study} results are consistent with those of [1] Tondjo *et al.* (2015) on the Teck, who claimed, on the
 281 basis of the ~~linear~~ relationship between the leaf area and the product of the length and width
 282 that ~~the leaves have a simple expansion~~ ^{expand} without change ⁱⁿ shape. We therefore conclude that
 283 both length and width measurements are necessary to estimate leaf area and dry mass
 284 accurately of cashew leaves, and the tree ^{location} ~~position~~ in the plantation affects the quantity of
 285 sunlight intercepted by the trees.

286

287 Conclusion

288 This aim of the study was firstly to assess the effect of the tree ^{location} ~~position~~ in the plantation on
 289 the characteristics (length, width, area, dry mass) of the cashew leaves, and secondly to ^{develop models}
 290 ^{to} estimate with good accuracy leaf area and dry mass of the leaves. The tree ^{location} ~~position~~ in the
 291 plantation had an influence on the ^{morphological} characteristics of the leaf, ^{and} including the leaf area and dry
 292 mass. The best models for estimating the leaf area and the dry mass of cashew leaves were ^a
 293 function of the logarithm of the product of the length and width, and ^{the model coefficients varied} ~~very~~ according to the tree

294 ^{location}
~~position~~ in the plantation. It therefore appears necessary to consider the ~~position~~^{location} of trees in
295 the sample design for ~~the estimation of leaf area~~^{estimating} and dry mass of the leaves ~~at~~ⁱⁿ a plantation,
296 and ~~in default to develop~~^{the} specific model ~~for each position of the trees according~~^{coefficients to location in relation to}
297 ~~movement~~^{incidence} of the solar radiation.

298 **References**

299 1. Tondjo K, Brancheriau L, Sabatier SA, Kokutse AD, Akossou A, Kokou K, Fourcaud
300 T. Non-destructive measurement of leaf area and dry biomass in *Tectona grandis*.
301 *Trees*, 2015, 29(5): 1625–1631.

302 2. Marron N, Villar M, Dreyer E, Delay D, Boudouresque E, Petit J-M, Delmotte FM,
303 Guehl J-M, Brignolas F. Diversity of leaf traits related to productivity in 31 *Populus*
304 *deltoides* x *Populus nigra* clones. *Tree Physiol*, 2005, 25: 425–435.

305 3. Blanco FF, Folegatti MV. Estimation of leaf area for greenhouse cucumber by linear
306 measurements under salinity and grafting. *Agricultural Science*, 2005, 62(4): 305–
307 309.

308 4. Lang GA. Precocious, dwarfing and productive – How will new cherry rootstocks
309 impact the sweet cherry industry? *HortTechnol.*, 2000, 10: 719–725.

310 5. Lang GA. Underlying principles of high density sweet cherry production, *Acta Hortic.*
311 2005, 667: 325–335.

312 6. Fourcaud T, Zhang XP, Stokes A, Lambers H, Koerner C. Plant growth modelling
313 and applications: the increasing importance of plant architecture in growth models.
314 *Ann. Bot.* 2008, 101: 1053–1063.

315 7. Kvet J, Marshall JK. Assessment of leaf area and other assimilating plant surfaces. In
316 Z. Sestak, J. Catsky, and P. G. Jarvis, Eds., *Plant Photosynthetic Production*, Manual
317 of Methods, Junk Publishers, The Hague, The Netherlands, 1971, 517–555.

- 318 8. Lu HY, Lu CT, Wei ML, Chan LF. Comparison of different models for non-
319 destructive leaf area estimation in taro. *Agronomy Journal*, 2004, 96(2): 448–453.
- 320 9. Stewart DW, Dwyer LM. Mathematical characterization of leaf shape and area of
321 maize hybrids. *Crop Science*, 1999, 39(2): 422–427.
- 322 10. Bhatt M, Chanda SV. Prediction of leaf area in *Phaseolus vulgaris* by non-destructive
323 method. *Bulgarian Journal of Plant Physiology*, 2003, 29(2): 96–100.
- 324 11. Mendoza-de Gyves E, Roupheal Y, Cristofori V, Mira FR. A non-destructive, simple
325 and accurate model for estimating the individual leaf area of kiwi (*Actinidia*
326 *deliciosa*). *Fruits*, 2007, 62(3): 171–176.
- 327 12. Kandiannan K, Parthasarathy U, Krishnamurthy KS, Thankamani CK, Srinivasan V.
328 Modelling individual leaf area of ginger (*Zingiber officinale* Roscoe) using leaf length
329 and width. *Scientia Horticulturae*, 2009, 120(4): 532–537.
- 330 13. Roupheal Y, Mouneimne AH, Rivera CM, Cardarelli M, Marucci A, Colla G.
331 Allometric models for non-destructive leaf area estimation in grafted and ungrafted
332 watermelon (*Citrullus lanatus* Thunb), *Journal of Food, Agriculture and*
333 *Environment*, 2010, 8(1): 161–165.
- 334 14. Montero FJ, De Juan Cuesta JA, Brasa A. Non-destructive methods to estimate leaf
335 area in *Vitis vinifera* L. *HortScience*, 2000, 35(4): 696–698.
- 336 15. Williams L, Martinson III TE. Non-destructive leaf area estimation of “Niagara” and
337 “Dechaunac” grapevines. *Scientia Horticulturae*, 2003, 98(4) : 493–498.
- 338 16. Uzun S, Celik H. Leaf area prediction models for different horticultural plants.
339 *Tropical Journal and Agricultural Forest*, 1999, 23(6): 645–650.
- 340 17. Projet d’Amélioration et de Diversification des Systèmes d’Exploitation (PADSE).
341 Diagnostic global de la filière anacarde au Bénin. *Rapport*, MAEP/PADSE, Bénin,
342 2003.

- 343 18. Tandjiékpon AM. *Analyse de la chaîne de valeur du secteur anacarde du Bénin.*
344 *Rapport d'étude*, Initiative du Cajou Africain (ICA/GIZ), Bénin, 2010.
- 345 19. De Swart EAM, Groenwold R, Kanne HJ, Stam P, Marcelis LFM, Voorrips RE. Non-
346 destructive estimation of leaf area for different plant ages and accessions of *Capsicum*
347 *annuum* L. *Journal of Horticultural Science & Biotechnology*, 2004, 79 (5): 764–770.
- 348 20. Poethig RS. Leaf morphogenesis in flowering plants. *The Plant Cell*, 1997, 9: 1077–
349 87.
- 350 21. Esau K. The leaf. In: Esau, K., eds. *Plant anatomy*. John Wiley and sons. New York,
351 London, Sidney, 1965, 467–80.
- 352 22. Byrne M, Timmermans M, Kidner C, Martienssen R. Development of leaf shape.
353 *Current Opinion in Plant Biology*, 2001, 4: 38–43.
- 354 23. Archak S, Ambika B, Gaikwad D, Gautam EV, Rao VB, Swamy KRM, Karihaloo JL.
355 DNA fingerprinting of India cashew (*Anacardium occidentale* L.), varieties using
356 RAPD and ISSR techniques, *Euphytica*, 2003, 130: 397-404.
- 357 24. Jones HG. *Plants and microclimate. A quantitative approach to environmental plant*
358 *physiology*. 3rd edn. Cambridge: Cambridge University Press, 1992.
- 359 25. Deneroy P, Thiebeau P, Goss G. Une méthode pour estimer l'interception du
360 rayonnement par un couvert bas: application au colza avant montaison. *Oléagineux,*
361 *Corps Gras, Lipides*, 2002, 9(1): 54-63.
- 362 26. Niinemets Ü, Portsmouth A, Tena D., Tobias M, Matesanz S, Valladares F. Do we
363 underestimate the importance of leaf size in plant economics? Disproportional scaling
364 of support costs within the spectrum of leaf physiognomy, *Annals of Botany*, 2007,
365 100 (2): 283-303.

- 366 27. Wardlaw CW. Leaves and buds: further observations. In: Wardlaw, CW, eds.
367 *Morphogenesis in plants. A contemporary study*. Methuen & Co TLD, London, UK,
368 1968, 181–225.
- 369 28. Verwijst T, Wen DZ. Leaf allometry of *Salix viminalis* during the first growing
370 season. *Tree Physiology*, 1996, 16: 655–60.
- 371 29. Leroy C, Guérault M, Wahyuni NS, Escoute J, Céréghino R, Sabatier S, Auclair D.
372 Morphogenetic trends in the morphological, optical and biochemical features of
373 phyllodes in *Acacia mangium* Willd (Mimosaceae). *Trees Struct Funct*, 2008, 23(1):
374 37–49.
- 375 30. Murthy KN, Kumar KV, Bhagavan S, Subbaiah CC, Kumaran PM. A rapid non-
376 destructive method of estimating leaf area in cashew. *Acta Horticulturae*, 1985, 108:
377 46-48.
- 378 31. Potdar MV, Pawar KR. Non-destructive leaf area estimation in banana, *Sci. Hortic.*
379 1991, 45: 251–254.
- 380 32. Bange MP, Hammer GL, Milroy SP, Rickert KG. Improving estimates of individual
381 leaf area of sunflower. *Agronomy Journal*, 2000, 92: 761–5.
- 382 33. Kandiannan K, Kailasam C, Chandaragiri KK, Sankaran N. Allometric model for leaf
383 area estimation in black pepper (*Piper nigrum* L.). *J. Agric. Crop. Sci.*, 2002,
384 188:138–140.
- 385 34. Souza EF, Araújo MC, Posse RP, Detmann E, Bernardo S, Berbert PA, Santos PA.
386 Estimating the total leaf area of the green dwarf coconut tree (*Cocos nucifera* L.). *Sci.*
387 *Agric.*, 2005, 62: 597-600.
- 388 35. Pompelli MF, Antunes WC, Ferreira DTRG, Cavalcante PGS, Wanderley-Filho HCL,
389 Endres L. Allometric models for non-destructive leaf area estimation of *Jatropha*
390 *curcas*. *Biomass and Bioenergy*, 2012, 36: 77-85.

391 36. Reynolds SGA. A note on estimation of leaf areas of Cacao (*Theobroma cacao* L.)
392 from three leaf parameters, *Trop. Agric.* 1971, 48: 177–179.
393 37. Kobayashi KD. Estimating leaf area of ‘Beaumont’ guava, *Trop. Agric.* 1988, 65:
394 173–175.
395 38. Willaume M, Lauri PE, Sinoquet H. Light interception in apple trees influenced by
396 canopy architecture manipulation. *Trees*, 2004, 18:705–713

397
398 (Anacardium occidentale)
399 The Table 1: Different forms of regression models tested to estimate leaf area and dry mass
for cashew trees near Parakou, Benin.

Model	Equation	
	Leaf area	Dry mass
1	$S^{\lambda} = aLW + b$	$m^{\lambda} = aLW + b$
2	$S^{\lambda} = a\ln(LW) + b$	$m^{\lambda} = a\ln(LW) + b$
3	$S^{\lambda} = aL + b$	$m^{\lambda} = aL + b$
4	$S^{\lambda} = a\ln(L) + b$	$m^{\lambda} = a\ln(L) + b$
5	$S^{\lambda} = aW + b$	$m^{\lambda} = aW + b$
6	$S^{\lambda} = a\ln(W) + b$	$m^{\lambda} = a\ln(W) + b$
7	$S^{\lambda} = aL^2 + b$	$m^{\lambda} = aL^2 + b$
8	$S^{\lambda} = aW^2 + b$	$m^{\lambda} = aW^2 + b$

400 S = leaf area, m = quantity of dry mass, L = length of leaf, W = width of leaf, λ = coefficient maximizing Box-Cox transformation, $\ln$ =
401 natural logarithm, a , b = constant to be estimated.

402

403 Table 2: Description of the ^{leaf} characteristics of cashew trees (*Anacardium occidentale*)
near Parakou, Benin.

Characteristics	Tree position	Mean	Mean error	Coefficient of Variation	Minimum	Maximum
Length (cm)	Center	15.28	0.15	18.80	4.50	25.00
	East	14.06	0.14	18.59	4.80	20.60
	North	15.49	0.14	16.71	7.50	22.30
	West	13.70	0.12	16.32	2.50	20.30
	South	15.02	0.15	18.40	8.80	24.00
Width (cm)	Center	8.45	0.08	17.70	5.30	14.00
	East	8.57	0.08	18.75	3.80	13.80
	North	8.44	0.08	16.87	3.90	12.20
	West	8.37	0.07	15.38	5.70	12.20
	South	9.60	0.09	18.56	5.20	14.70
Area (cm ²)	Center	96.42	1.88	36.98	32.44	234.18
	East	66.77	1.29	36.34	12.73	155.80
	North	91.79	1.70	34.81	29.36	198.78
	West	71.41	1.19	31.30	17.52	139.17
	South	109.14	2.11	36.66	34.61	251.49
Dry mass (g)	Center	1.19	0.02	31.78	0.50	2.47
	East	1.24	0.03	40.01	0.18	3.47
	North	1.19	0.02	32.44	0.38	2.49
	West	1.03	0.02	32.81	0.21	2.06
	South	1.29	0.02	35.02	0.35	2.90

404

405

406 Table 3: Comparison of average values of the characteristics of the ^{leaf} cashew trees (*Anacardium occidentale*)
407 position in the planting ^{by tree location in a plantation near Parakou, Benin.}

Position	Length (cm)	Width (cm)	Area (cm ²)	Dry mass (g/leaf)
South	15 ^a	9.6 ^a	109.1 ^a	1.3 ^a
Center	15.3 ^a	8.5 ^b	96.4 ^b	1.2 ^b
North	15.5 ^a	8.4 ^b	91.9 ^b	1.2 ^b
East	14.1 ^b	8.6 ^b	66.7 ^c	1.2 ^{ab}
West	13.7 ^b	8.4 ^b	71.4 ^c	1.0 ^c

408

For a given characteristic, mean sharing no letter are significantly different at the 5% level.

409

410 Table 4: Prediction models ^{for} of cashew trees (*Anacardium occidentale*) ^{location} by ~~leaf area according to the tree position in the plantation~~ near Parakou, Benin.

Tree Position in plantation	Model	λ max	Parameters		Adjustment parameters			Prediction error
			a	b	F	p	Raj	
Center	$S^c = aLW + b$	0.274	0.006	2.657	734.1	0.00	0.67	0.0385
	$S^c = aln(LW) + b$	0.032	0.033	0.996	818.2	0.00	0.70	0.0001
	$S^c = aL + b$	0.087	0.013	1.281	615.3	0.00	0.63	0.0008
	$S^c = aln(L) + b$	-0.041	-0.054	0.975	620.3	0.00	0.63	0.0001
	$S^c = aW + b$	0.171	0.069	1.581	540.0	0.00	0.60	0.0071
	$S^c = aln(W) + b$	0.081	0.187	1.043	549.3	0.00	0.61	0.0007
	$S^c = aL^2 + b$	0.211	0.002	2.184	577.4	0.00	0.62	0.0151
	$S^c = aW^2 + b$	0.248	0.008	2.499	497.0	0.00	0.58	0.0319
East	$S^e = aLW + b$	0.428	0.016	3.931	495.70	0.00	0.59	0.3541
	$S^e = aln(LW) + b$	0.119	0.145	0.948	473.00	0.00	0.57	0.0021
	$S^e = aL + b$	0.256	0.076	1.826	412.20	0.00	0.54	0.0334
	$S^e = aln(L) + b$	0.092	0.182	0.985	394.50	0.00	0.53	0.0011
	$S^e = aW + b$	0.295	0.165	2.001	381.80	0.00	0.52	0.0640
	$S^e = aln(W) + b$	0.174	0.484	1.027	371.00	0.00	0.51	0.0083
	$S^e = aL^2 + b$	0.389	0.007	3.593	419.20	0.00	0.54	0.2327
	$S^e = aW^2 + b$	0.401	0.020	3.814	378.10	0.00	0.52	0.2891
North	$S^n = aLW + b$	0.437	0.025	3.839	1886.00	0.00	0.84	0.1922
	$S^n = aln(LW) + b$	-0.088	-0.062	0.974	2249.00	0.00	0.86	0.0001
	$S^n = aL + b$	0.334	0.187	1.566	1473.00	0.00	0.81	0.0546
	$S^n = aln(L) + b$	0.110	0.348	0.688	1510.00	0.00	0.81	0.0008
	$S^n = aW + b$	0.097	0.033	1.262	1074.00	0.00	0.75	0.0007
	$S^n = aln(W) + b$	-0.135	-0.137	0.839	1181.00	0.00	0.77	0.0002
	$S^n = aL^2 + b$	0.536	0.023	5.322	1372.00	0.00	0.79	0.9056
	$S^n = aW^2 + b$	0.293	0.014	2.699	931.70	0.00	0.72	0.0414
West	$S^w = aLW + b$	0.555	0.037	6.199	354.30	0.00	0.50	1.7200
	$S^w = aln(LW) + b$	0.418	1.894	-3.046	372.90	0.00	0.51	0.2978
	$S^w = aL + b$	0.419	0.237	2.676	258.50	0.00	0.42	0.3593
	$S^w = aln(L) + b$	0.362	2.216	-1.142	265.80	0.00	0.43	0.1623
	$S^w = aW + b$	0.534	0.908	2.076	370.20	0.00	0.51	1.3046
	$S^w = aln(W) + b$	0.462	4.880	-3.208	368.80	0.00	0.51	0.5283
	$S^w = aL^2 + b$	0.469	0.011	5.142	243.00	0.00	0.41	0.7021
	$S^w = aW^2 + b$	0.602	0.078	7.338	359.60	0.00	0.50	2.9732
South	$S^s = aLW + b$	0.485	0.026	5.787	401.00	0.00	0.53	1.4494
	$S^s = aln(LW) + b$	0.314	1.054	-0.899	407.50	0.00	0.53	0.1238
	$S^s = aL + b$	0.434	0.309	2.885	337.30	0.00	0.48	0.7835
	$S^s = aln(L) + b$	0.354	2.520	-1.603	325.30	0.00	0.48	0.2537
	$S^s = aW + b$	0.388	0.328	2.932	272.00	0.00	0.43	0.4551
	$S^s = aln(W) + b$	0.322	1.836	0.339	271.90	0.00	0.43	0.1697
	$S^s = aL^2 + b$	0.516	0.018	6.968	332.70	0.00	0.48	2.3817
	$S^s = aW^2 + b$	0.448	0.025	5.631	255.00	0.00	0.42	1.0869

S = area, L = length, W = width, λ = coefficient maximizing the Box-Cox transformation, ln = natural logarithm, a , b = constant estimate.

413

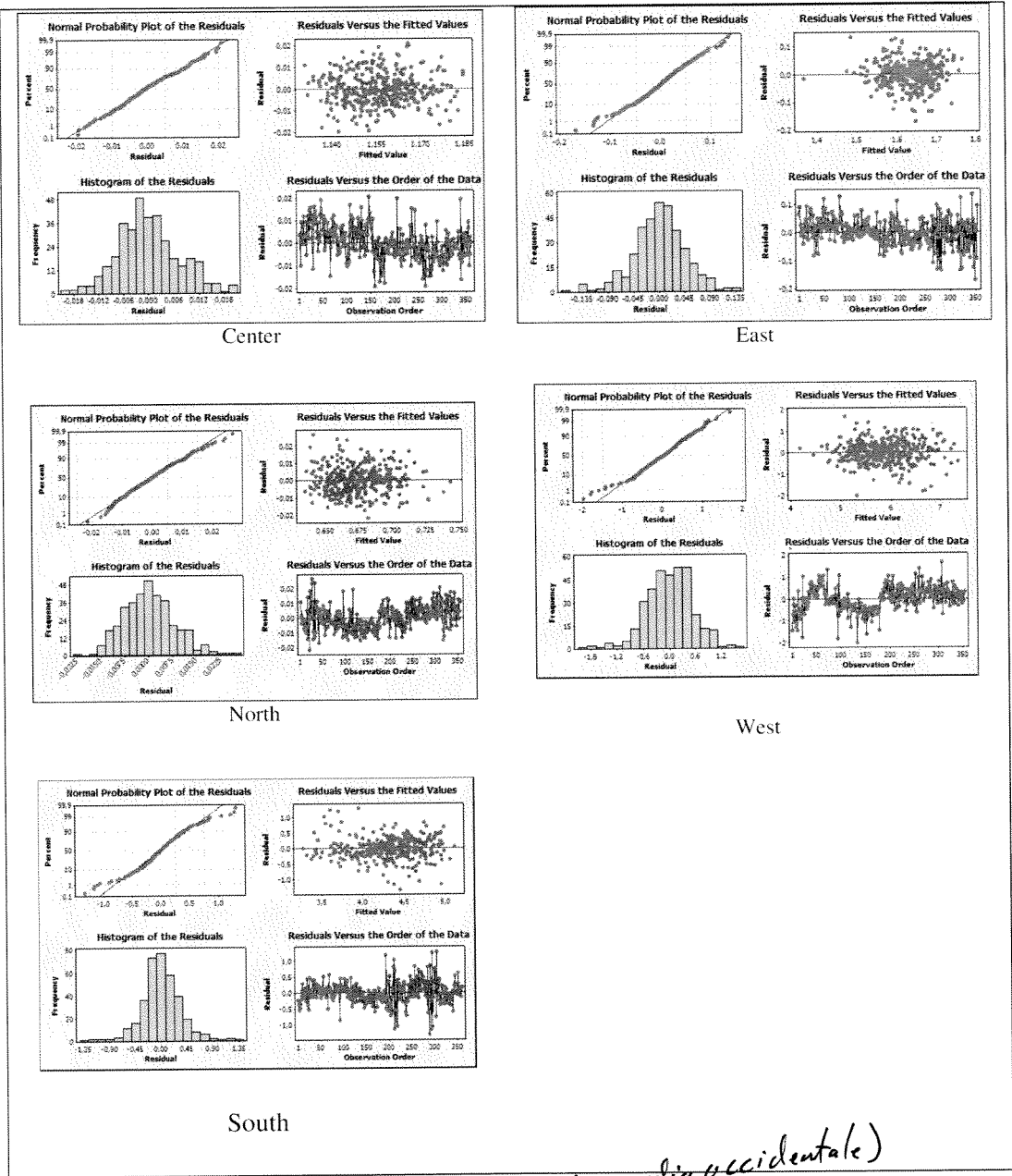
Table 5: Prediction models for leaf dry mass according to the tree location in the plantation near Parakou, Benin

Tree position in plantation	Model	λ max	Parameters		Adjustment parameters			Prediction error
			a	b	F	p	Raj	
Center	$m^{\hat{}} = aLW + b$	0.399	0.001	0.871	593.10	0.00	0.63	0.00186
	$m^{\hat{}} = aln(LW) + b$	0.075	-0.043	1.199	688.50	0.00	0.66	0.00011
	$m^{\hat{}} = aL + b$	0.097	-0.002	1.023	465.60	0.00	0.57	0.00002
	$m^{\hat{}} = aln(L) + b$	-0.061	-0.204	1.535	495.70	0.00	0.58	0.00100
	$m^{\hat{}} = aW + b$	0.328	0.027	0.793	510.90	0.00	0.59	0.00115
	$m^{\hat{}} = aln(W) + b$	0.188	0.069	0.860	519.00	0.00	0.59	0.00010
	$m^{\hat{}} = aL^2 + b$	0.228	0.000	0.953	417.80	0.00	0.54	0.00043
East	$m^{\hat{}} = aLW + b$	0.451	0.002	0.859	475.60	0.00	0.57	0.00322
	$m^{\hat{}} = aLW + b$	0.515	0.004	0.551	912.90	0.00	0.73	0.0134
	$m^{\hat{}} = aln(LW) + b$	0.037	0.247	-0.136	1020.00	0.00	0.75	0.0028
	$m^{\hat{}} = aL + b$	0.268	0.049	0.374	682.30	0.00	0.67	0.0081
	$m^{\hat{}} = aln(L) + b$	0.026	0.417	-0.057	691.60	0.00	0.67	0.0033
	$m^{\hat{}} = aW + b$	0.343	0.090	0.300	764.80	0.00	0.69	0.0093
	$m^{\hat{}} = aln(W) + b$	0.149	0.544	-0.112	782.40	0.00	0.69	0.0049
North	$m^{\hat{}} = aL^2 + b$	0.450	0.002	0.625	637.30	0.00	0.65	0.0146
	$m^{\hat{}} = aLW + b$	0.510	0.006	0.609	698.80	0.00	0.67	0.0155
	$m^{\hat{}} = aLW + b$	0.454	0.005	0.405	779.40	0.00	0.69	0.0221
	$m^{\hat{}} = aln(LW) + b$	0.122	0.493	-1.302	771.20	0.00	0.69	0.0116
	$m^{\hat{}} = aL + b$	0.332	0.070	0.018	569.30	0.00	0.62	0.0195
	$m^{\hat{}} = aln(L) + b$	0.194	0.921	-1.424	568.70	0.00	0.62	0.0146
	$m^{\hat{}} = aW + b$	0.287	0.128	0.019	627.10	0.00	0.64	0.0181
West	$m^{\hat{}} = aln(W) + b$	0.131	0.888	-0.797	611.00	0.00	0.64	0.0134
	$m^{\hat{}} = aL^2 + b$	0.454	0.003	0.500	550.40	0.00	0.61	0.0255
	$m^{\hat{}} = aLW + b$	0.431	0.009	0.488	607.30	0.00	0.63	0.0243
	$m^{\hat{}} = aLW + b$	0.687	0.006	0.309	1320.00	0.00	0.79	0.0115
	$m^{\hat{}} = aln(LW) + b$	0.352	0.530	-1.500	1403.00	0.00	0.80	0.0060
	$m^{\hat{}} = aL + b$	0.405	0.069	0.050	835.80	0.00	0.71	0.0092
	$m^{\hat{}} = aln(L) + b$	0.239	0.799	-1.084	865.80	0.00	0.72	0.0062
South	$m^{\hat{}} = aW + b$	0.572	0.145	-0.204	1029.00	0.00	0.75	0.0116
	$m^{\hat{}} = aln(W) + b$	0.447	1.085	-1.288	1026.00	0.00	0.75	0.0091
	$m^{\hat{}} = aL^2 + b$	0.547	0.003	0.473	767.50	0.00	0.69	0.0128
	$m^{\hat{}} = aLW + b$	0.695	0.009	0.356	969.00	0.00	0.74	0.0149
	$m^{\hat{}} = aLW + b$	0.431	0.002	0.854	138.10	0.00	0.28	0.0152
	$m^{\hat{}} = aln(LW) + b$	0.390	0.200	0.084	155.80	0.00	0.30	0.0116
	$m^{\hat{}} = aL + b$	0.391	0.024	0.709	130.10	0.00	0.27	0.0125
South	$m^{\hat{}} = aln(L) + b$	0.368	0.340	0.153	141.30	0.00	0.28	0.0106
	$m^{\hat{}} = aW + b$	0.444	0.041	0.694	108.60	0.00	0.23	0.0177
	$m^{\hat{}} = aln(W) + b$	0.431	0.367	0.262	110.40	0.00	0.23	0.0166
	$m^{\hat{}} = aL^2 + b$	0.412	0.001	0.890	115.60	0.00	0.24	0.0146
	$m^{\hat{}} = aLW + b$	0.456	0.002	0.888	100.60	0.00	0.22	0.0192

m = mass, L = length, W = width, λ = coefficient maximizing the Box-Cox transformation, ln = natural logarithm, a , b = constant estimate.

414

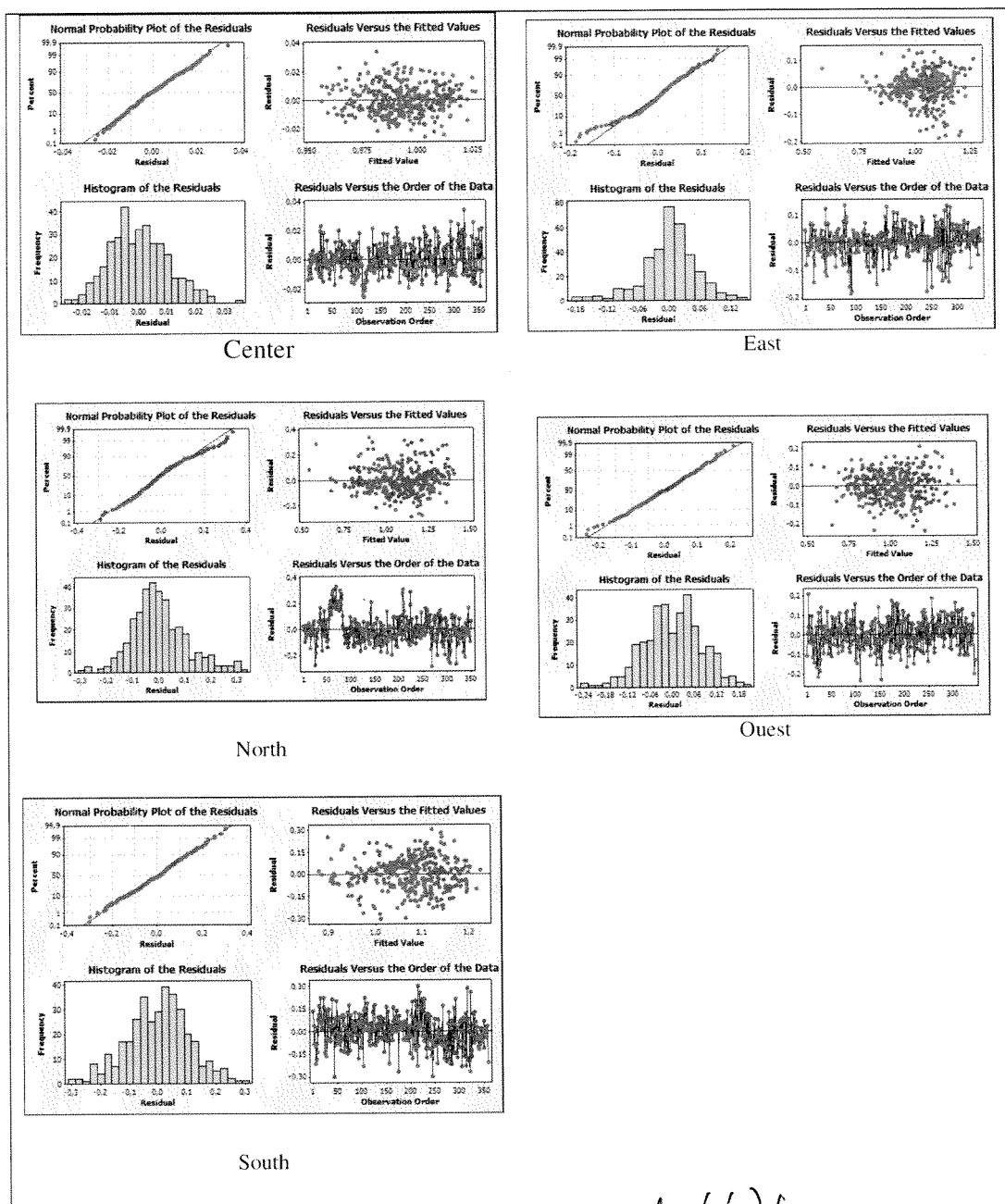
415



416

417

Figure 1. Diagnostics of residuals from the regression of leaf area models by location in a plantation near Parkou, Benin.



418

419

420

cashew tree (*Anacardium occidentale*) leaf
 Figure 2. Diagnostics of residuals from the regression of dry mass according to tree position in a
 plantation near Parakou, Benin